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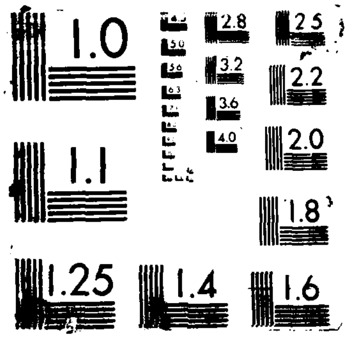
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EFFECT OF SAMPLE VOLUME ON QUANTITATION OF FERROGRAPHIC DATA

Robert L. Wright and Phillip W. Centers, Ph.D.
Lubrication Branch
Fuels and Lubrication Division

March 1988

Final Report for Period July 1987 - December 1987

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Previous investigators assumed that ferrographic area coverage data were linearly related to quantity of sample analyzed. However, theoretical examination of ferrographic deposition of wear debris and treatment of published data confirm that coverage varies with sample quantity by a power law relationship. Improved normalization and wear trending procedures based upon power curve fitting of area covered measurements versus sample quantities are developed. The new procedures should increase confidence and reliability in both ferrographic measurement and wear severity index trending.

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PREFACE

This technical report was prepared by the Lubrication Branch, Fuels and Lubrication Division, Aero Propulsion Laboratory (APL), Air Force Wright Aeronautical Laboratories (AFWAL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio. The work herein was accomplished under Project 3048, Task 304806, Work Unit 30480626, "Turbine Engine Lubricant Research," during the period of July 1987 to December 1987 with Mr Robert L. Wright and Dr Phillip W. Centers as Project Engineers.

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SECTION I

INTRODUCTION

For the analytical quantitation of wear debris, i.e., percent area covered (PAC) per milliliter of sample in a microscopic field of view) found in fluid systems by ferrographic techniques, the commonly employed normalization procedure ~~(ref 1)~~ used for variations in sample volume is a linear relationship. In practice, sample dilutions are made or sample volumes are increased until a ferrogram is obtained with 10 to 40 PAC as recommended for quantitative purposes. However, at this level of PAC, localized piling of debris has been observed which suggests that the use of a linear relationship would be inappropriate. Evaluation of theory as well as close examination of PAC versus sample volume or sample dilution data reported by others suggest that the correct relationship would be a power law, which would be valid for very dilute samples as well as more concentrated ones.

Establishing a valid normalization relationship is critical for effective use of wear severity indexes (ref 2, 3) currently employed in ferrographic assessment of machinery health. If incorrectly applied, such wear severity indexes may cause premature removal of equipment or not identify a failing unit in time to prevent catastrophic failure. Therefore, a theoretical and data treatment study of percent area covered as a function of amount of sample analyzed was conducted to improve the analytical capabilities of and confidence in ferrography as a diagnostic tool.

SECTION II

THEORY

Let us consider an analytical ferrograph (AF) slide (ferrogram) as it rests on the magnetic platform of the instrument during preparation. In the first instance, the deposition of a small amount of ferrous wear debris may be viewed as particles being laid down on the ferrogram in thin lines along the instrument's magnetic lines of force. One may then treat these thin lines of debris as minute halves of right circular cylinders. Postulating for a single line of debris of length, l, one can see that the change of surface area covered (A) on the ferrogram with respect to debris volume (V) is inversely proportional to the magnitude of the cylinder radius, r. This A versus V relationship is a perfect power law function of the form:

$$A = aV^b \tag{1}$$

where a is a proportionality constant and b is an exponent that determines curve shape. A plot of relative A versus relative V for the magnitude of r varying from zero to one and l equal to unity is shown in Figure 1.

Secondly, the deposition of more concentrated ferrous wear debris over a small circular cross-section of the ferrogram may be simply viewed as the volume of a spherical segment bounded below by the plane of the ferrogram substrate. If one assumes that the magnetic field strength throughout this small cross-section is uniform and that the sphere radius, r, of this segment is the distance to the center of the magnetic field lying somewhere under the centerpoint of the collected debris, then one may arbitrarily

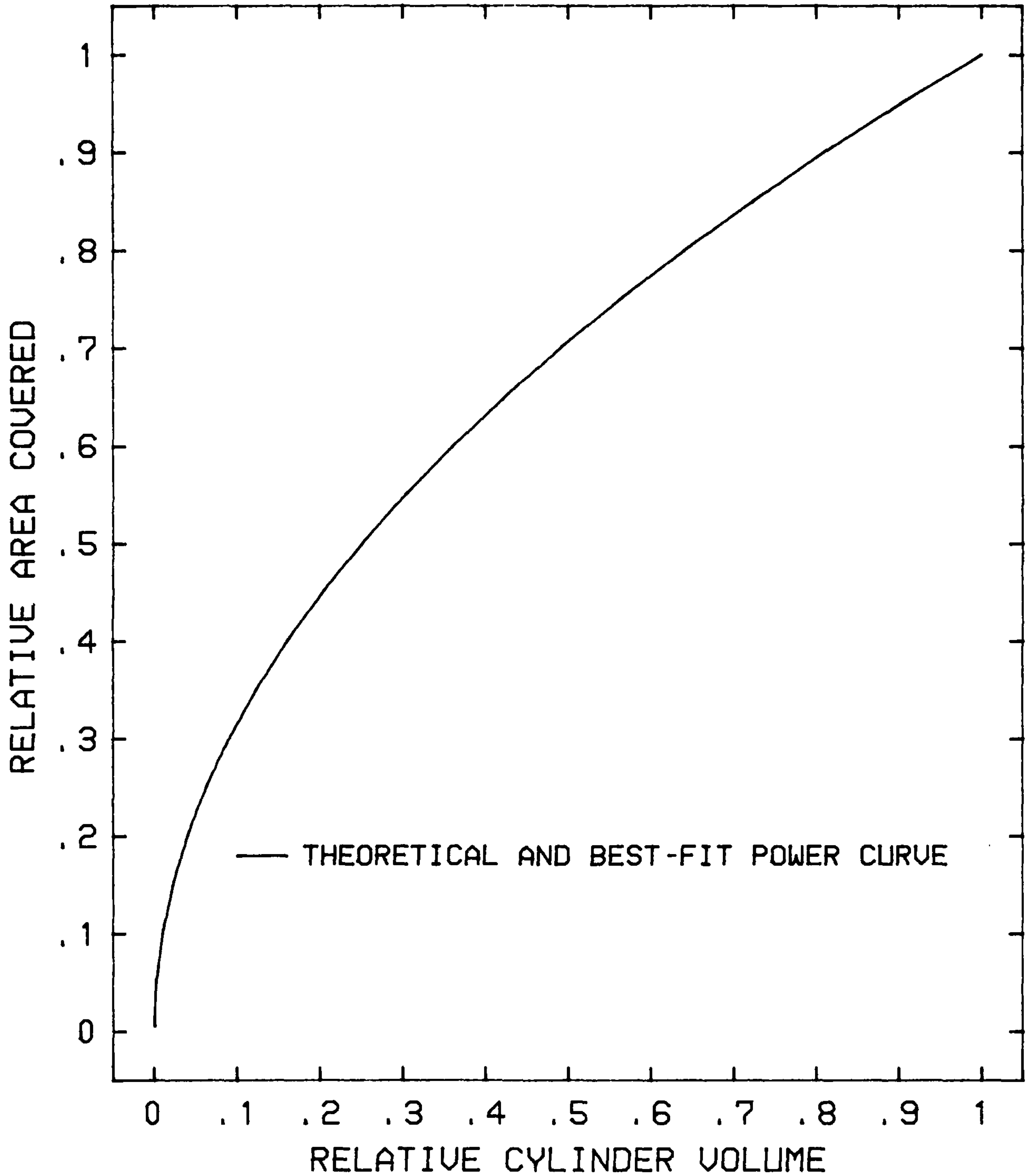


Figure 1. Relative area covered vs relative cylinder volume for $0 < r < 1$

assign the value of the length of the radius as unity and assume it is constant. The volume (V) of the segment can then be found by the mensuration formula:

$$V = \frac{\pi}{3}(h^2 r - h^3) \text{ or } V = \frac{\pi}{3}(h^2 - h^3), \text{ since } r = 1 \qquad (2)$$

where the variable, h, is the height of the volume segment above the ferrogram. One may insert values of h to find segment volumes, and after finding a number of these, one can calculate corresponding values of the surface area covered on the ferrogram cross-section by manipulation of another mensuration formula to find:

$$A = 2V/h - \pi h^2/3 \qquad (3)$$

A plot of relative surface area covered versus relative segment volume for the case of $0 < h/r < 0.01$ is shown in Figure 2. The theoretical curve shown is also the best fit power curve for this h/r range. The power curve equation is of the form of Equation 1. It can be shown that the power curve is an excellent approximation (coefficient of determination = 1.000) of the theoretical curve. The h/r range was chosen to be small because h is on the order of a few micrometers and r is several orders of magnitude greater. A similar treatment of the wear deposition situation in the direct reading (DR) ferrograph yields similar results.

Therefore, if this theoretical treatment of ferrous wear deposition is correct it would support use of the power law relationship for ferrographic quantitation as it is what one would expect from a two-dimensional measurement of a three-dimensional phenomena (surface area covered vs. volume of debris deposited).

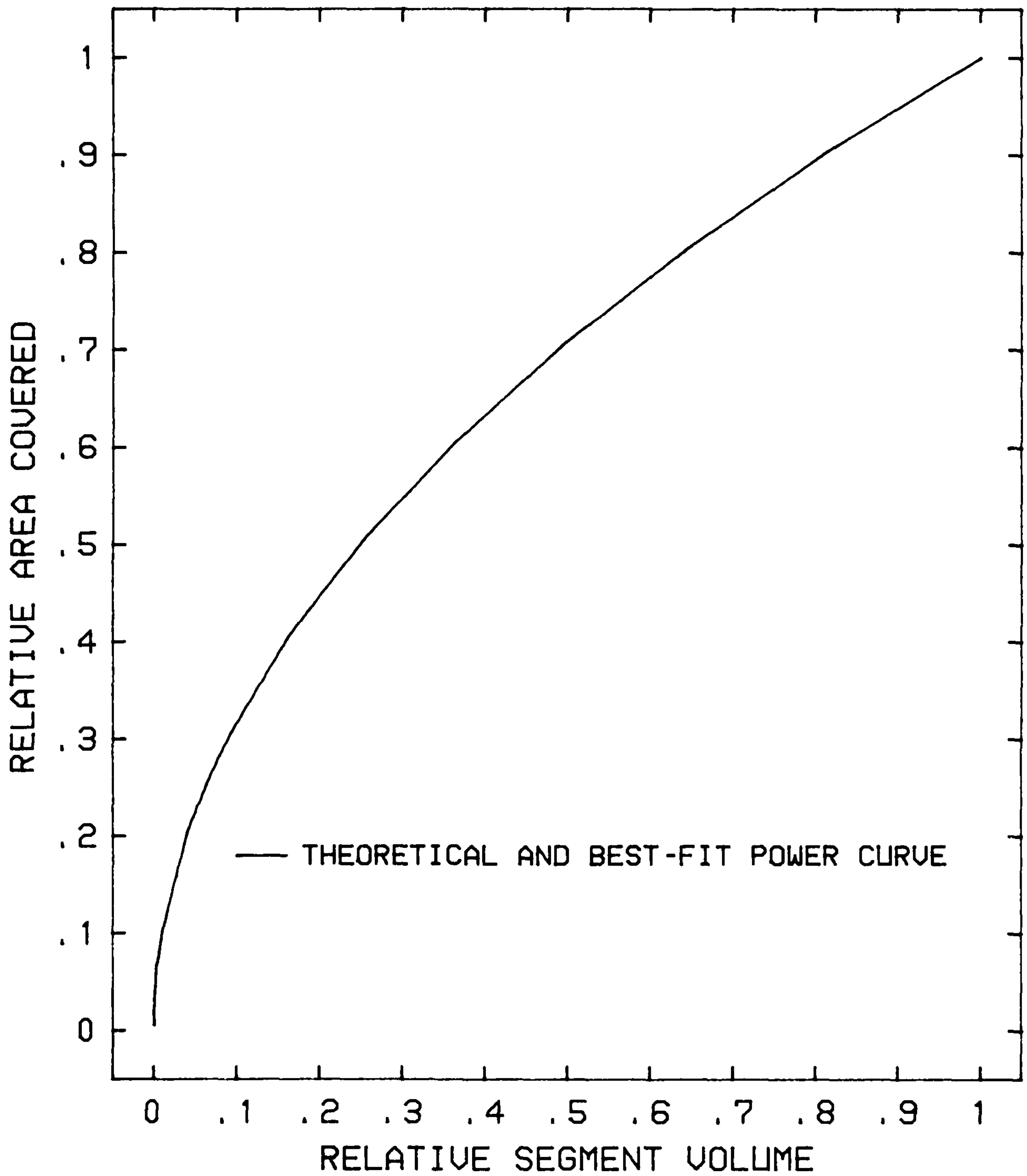


Figure 2. Relative area covered vs relative segment volume for $0 < h/r < 0.01$

SECTION III

TREATMENT OF EXPERIMENTAL DATA

Several studies (ref 1, 4, 5, 6, 7, 8) detailing the effect of quantity of sample analyzed on ferrographic area covered measurements have been made. To determine whether the linear relationship or the power law relationship presented here is more valid, data cited above were carefully examined. Three typical examples are shown. First, PAC versus sample volume data reported by Pocock and Courtney (ref 4) is shown in Figure 3. Secondly, PAC versus sample volume data from Tessmann (ref 5) is given in Figure 4. Thirdly, PAC versus sample dilution (n) data reported by Belmondo, et al. (ref 6) is presented in Figure 5. These data, as well as that of others for AF (ref 1, 7) and DR (ref 8), were correlated by linear regression and by power law curve fitting for both the preferred area covered ranges, i. e., $10 < PAC < 40$ for AF and $D_L < 100$, $D_S < 70$ for DR, and the full range of values reported.

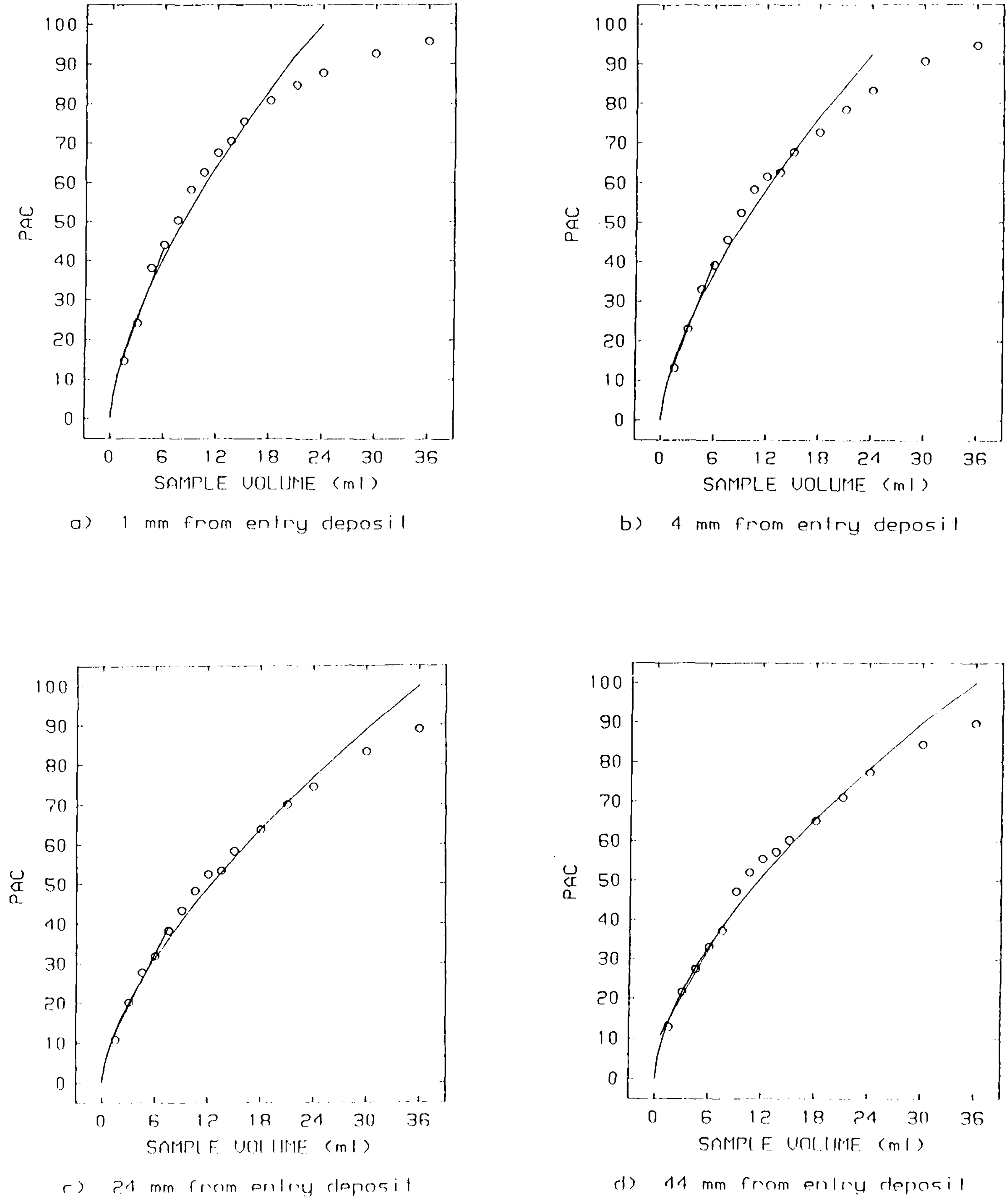


Figure 3. Analytical ferrograph PAC vs sample volume data reported by Pocock and Courtney

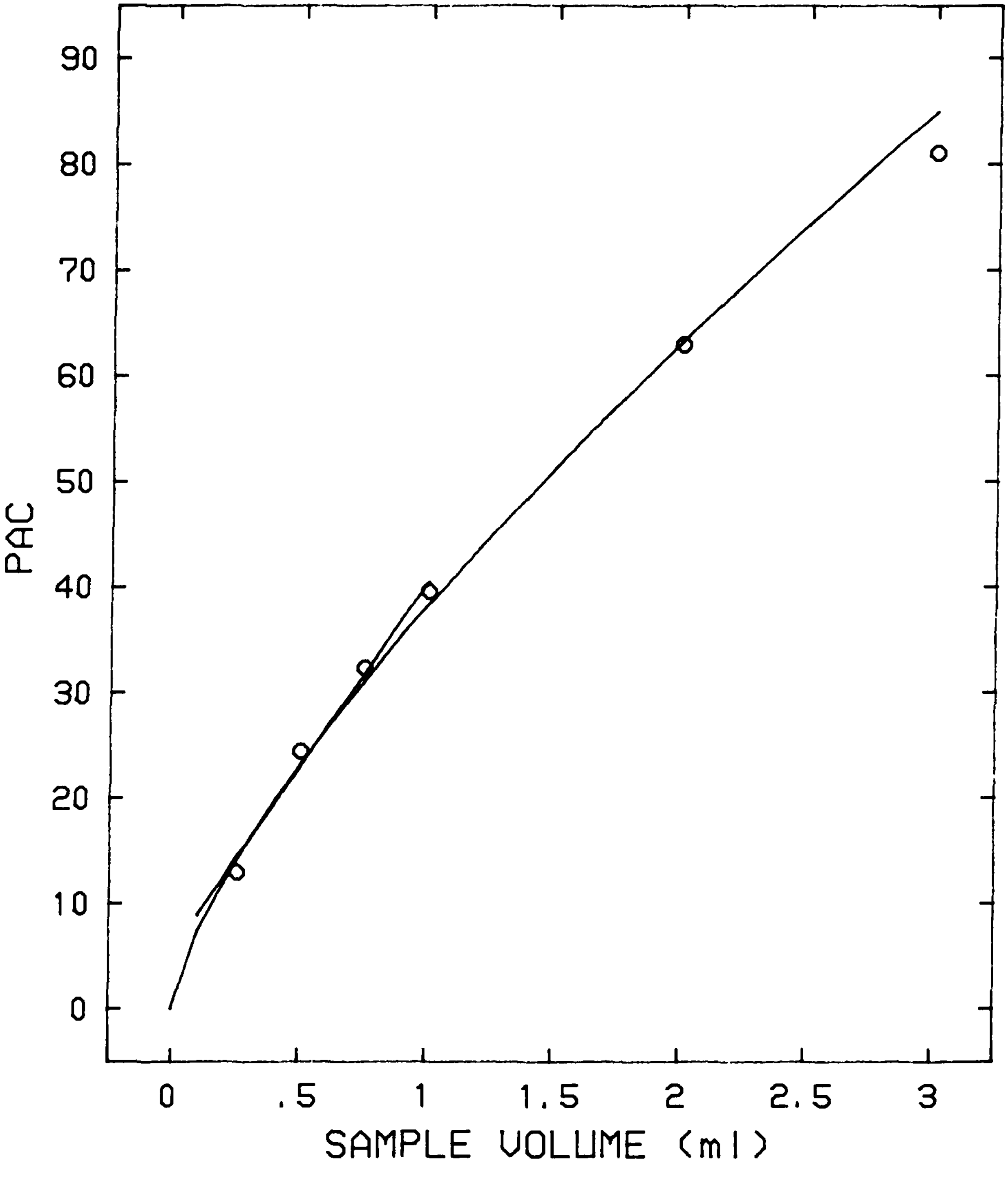
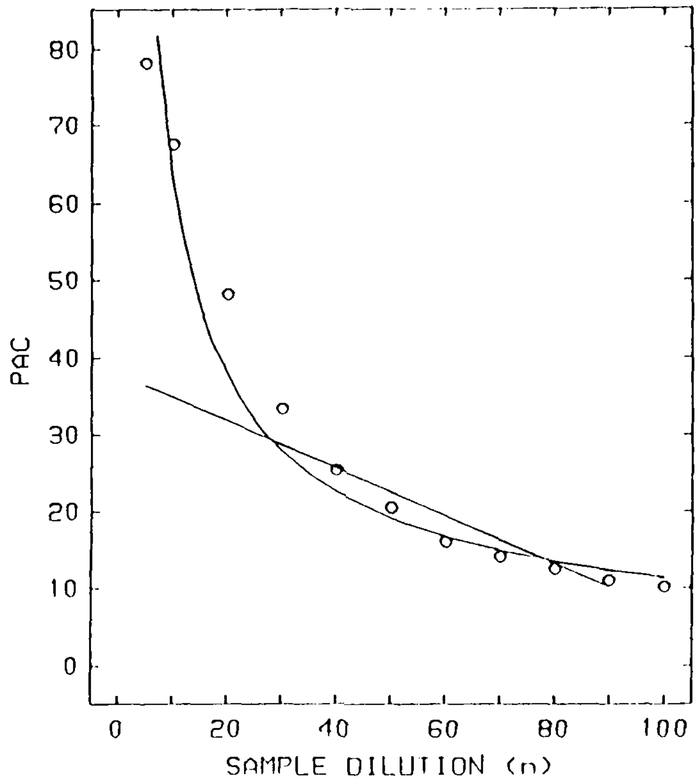
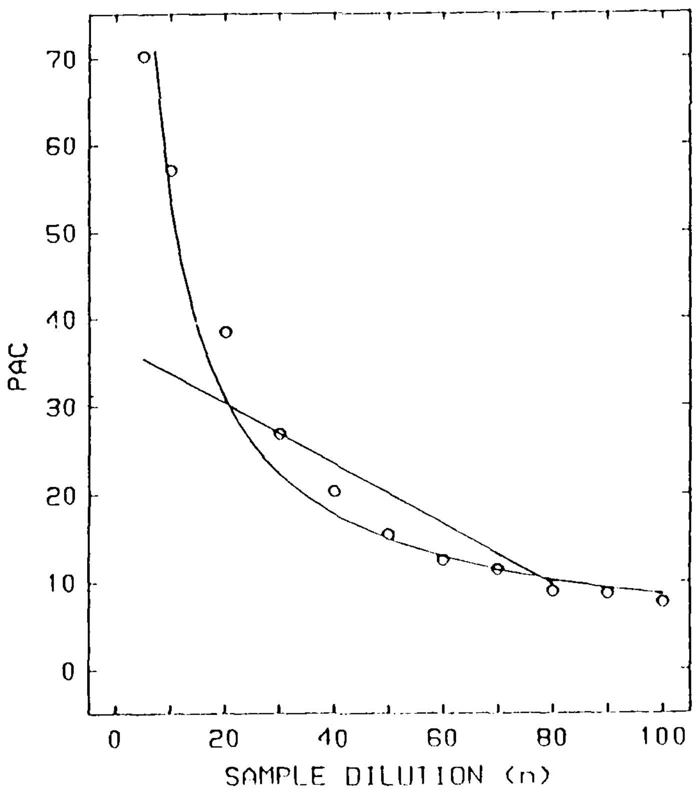


Figure 4. Analytical ferrograph PAC vs sample volume data at 54 mm from ferrogram exit reported by Tessmann



a) Entry deposit



b) 6 mm from entry deposit

Figure 5. Analytical ferrograph PAC vs sample dilution data reported by Belmondo, et al.

SECTION IV

RESULTS AND DISCUSSION

In Figures 3, 4 and 5, the reported data points are shown along with the best-fit power curve for the full PAC range and the best-fit straight line for the 10 to 40 PAC range. In these and all other data examined (ref 1, 7, 8) for AF and DR, a non-linear change in area covered with variation in quantity of sample analyzed is evident. There is always a decrease in the A/V slope as sample volume is increased or an increase in the A/n slope as sample dilution is increased, even in the generally preferred range of area coverage values.

Based upon the theoretical arguments presented earlier, the data shown in Figures 3, 4 and 5 should better fit a power law rather than a linear relationship. Table 1 gives a comparison of the coefficients of determination for the linear and power law correlations for each of the curves in these figures. The coefficient of determination is the proportionate reduction of total variation associated with the use of the independent variable (ref 9) and is equal to the square of the correlation coefficient. The coefficients of determination are shown calculated both for the 10 to 40 PAC preferred range and for the 0-90 PAC range of values reported. Above 90 PAC, the A/V slope is nearly horizontal (A/n slope nearly vertical) and PAC ceases to be a function of V or n. For all data reported as a function of sample volume (ref 1, 4, 5, 7), the power law correlation is slightly better than the linear correlation for the preferred area covered range and much better than the linear correlation for the full area covered range, while for data reported as a function of sample dilution

TABLE 1 COMPARISON OF COEFFICIENTS OF DETERMINATION FOR LINEAR AND POWER LAW CORRELATIONS

DATA	FERROGRAM POSITION	COEFFICIENT OF DETERMINATION 10-40 PAC RANGE LINEAR	POWER LAW	0-90 PAC RANGE LINEAR	POWER LAW
POCOCK et al.	1 mm FROM ENTRY	0.974	0.989	0.834	0.974
POCOCK et al.	4 mm FROM ENTRY	0.989	0.997	0.891	0.981
POCOCK et al.	24 mm FROM ENTRY	0.982	0.997	0.874	0.985
POCOCK et al.	44 mm FROM ENTRY	0.982	0.997	0.874	0.986
TESSMANN	54 mm	0.987	0.995	0.980	0.994
BELMONDO et al.	ENTRY POINT	0.884	0.998	0.813	0.954
BELMONDO et al.	6 mm FROM ENTRY	0.828	0.996	0.783	0.963

(ref 6, 8), power law correlation is far superior to linear correlation, regardless of area covered range. Note that when data is reported as a function of sample volume, linear correlations calculate a PAC value of greater than zero for sample volume equal to zero, due to the ever decreasing A/V slope, while power law correlations give a value of zero PAC at zero sample volume, as would a true model of the actual physical situation. This data treatment supports the hypothesis that the power law relationship is valid for ferrographic wear particle deposition. The restriction on area covered range (10 to 40 PAC), as used if a linear relationship is assumed, would not be necessary for power law correlation of data, because the power law relationship is valid for the entire range of values up to about 90 PAC.

Based upon these results, the power law relationship and curve fitting technique should improve reliability and confidence in the calculation of wear severity indexes (ref 2, 3) for samples that are analyzed at varying sample volumes. A valid procedure would be to analyze the lubricant by either AF or DR from equipment that is judged to be running normally (avoid break-in or wear-out cases) at several undiluted sample volumes, over a range that is likely to be used most often, to establish a reference. The oil to fixer ratio must remain constant for each of these analyses to fit the resulting reference data to the best power curve equation. Thereafter, for any sample volume analyzed, the data are normalized to one milliliter of undiluted sample by use of the following equation derived from Equation 1:

$$A_N = A/V^b \tag{5}$$

where A_N is the normalized area covered measurement, A is the unnormalized area covered measurement, V is the undiluted sample volume analyzed and b is the exponent found in the reference curve fitting analysis. After power law normalization, substitute the appropriate A_N's into the wear severity index equation which will then be more representative of the true wear trending situation in the equipment.

One sees in Equation 5 that A_N is a normalized measure of wear particle concentration. Direct, single measurement wear trending is accomplished by the following use of Equation 5:

$$A_{tN} = A_t/V^b \tag{6}$$

where A_{tN} is the normalized area covered measurement at time, t and A_t is the unnormalized area covered measurement at time, t. A plot of A_{tN} versus t will follow actual wear particle concentration as a function of time.

These power law correlation procedures for ferrographic quantitation provide more accurate wear trending based upon data generated by single measurements at the same position on ferrograms or for DR measurements while dual measurements such as those used to calculate wear severity indexes are also improved, since they rely on the theoretically and experimentally determined mode of ferrographic wear deposition presented here. Where a complete assessment of the wear debris content of a system is desired, power law correlation of ferrographic data also more correctly augments atomic emission spectrometer (AES) and in-line debris monitor (ILDM) trending of wear debris concentration since the ferrograph analyzes debris in sizes between those typically detected by both such methods (ref 10, 11).

SECTION V

CONCLUSIONS

Theoretical studies indicating a non-linear change in ferrographic area coverage measurements with variation in sample volume are confirmed by treatment of reported data. The power law relationship established is shown to be superior to linear correlations of reported data. A power law sample analysis and developed normalization procedure provides a basis for improved wear severity indexes and trending analyses and for augmentation of AES and ILDM trending.

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